Evaluating Shoreline Response to Offshore Sand Mining for Beach Nourishment

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ABSTRACT

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An analytical approach that incorporates analysis of nearshore wave transformation and wave-induced longshore sediment transport was developed to quantify the significance of potential physical environmental impacts associated with offshore sand mining. Calculation of longshore sediment transport potential for a series of wave cases provided a method for determining the extent and magnitude of alterations to nearshore processes, but the magnitude of change alone did not provide enough information to determine the significance of changes for a particular coastline. This paper documents a method for evaluating the significance of borrow site impacts that incorporates temporal and spatial variations in the incident wave field. Example applications of this method are presented for borrow sites offshore Oregon Inlet, North Carolina; Martin County, Florida; and Corsons Inlet, New Jersey. As a management tool, this methodology holds several advantages over methods previously employed to assess the significance of borrow site impacts, including: 1) a model-independent component (observed shoreline change) is used to verify model results; 2) impacts associated with borrow site excavation can be directly related to their potential influence on observed coastal processes; 3) site-specific temporal variability in wave climate and sediment transport potential is calculated as part of the methodology; and 4) the procedure accounts for spatial and temporal variability in wave climate, as well as provides a means of quantifying significance of impacts relative to site-specific conditions.

ADDITIONAL INDEX WORDS: *Wave transformation modeling, longshore sediment transport, cumulative effects, Oregon Inlet, North Carolina, Martin County, Florida, Corsons Inlet, New Jersey.*

INTRODUCTION

During the past few decades, there has been increased interest in sand and gravel resources on the Outer Continental Shelf (OCS) of the USA (*e.g.,* FIELD and DUANE, 1974; MEISBURGER and WILLIAMS, 1980; WILLIAMS, 1987). The potential for exploitation of these sand resources as a source for beach and barrier island restoration has grown rapidly as similar resources in State waters are being depleted or polluted. Beach nourishment, as a form of erosion control, has become a standard engineering alternative to coastal engineering structures (*e.g.* groins, seawalls, and breakwaters) because nourishment projects dissipate wave energy and replenish the local sediment supply.

However, beach nourishment programs potentially can cause adverse environmental impacts at beach fill locations and borrow sites if an offshore sediment source is mined. In addition to concerns regarding biological resources, the physical effects of offshore sand mining on the incident wave field and associated sediment transport regime may alter local shoreline change. This is demonstrated well in the example of a 1983 nourishment of Grand Isle, Louisiana (COMBE and SOILEAU, 1987) where a 2.1 million cubic meter (MCM) beach fill was constructed using sand from two borrow sites located 800 m offshore. Modifications to the wave and sediment transport climate of the area resulted in the unintended for-

7 received and accepted in revision 6 June 2003.

mation of large cuspate bars and erosion hot spots on the beach, which persisted long after the borrow sites had filled.

Many past offshore borrow site studies have used computer modeling of waves and shoreline change to determine post-dredging impacts (*e.g.,* HORIKAWA *et al.,* 1977; KRAUS *et al.,* 1988). Less attention has been focused on determining the relative significance of potential changes to the physical environment associated with offshore sand mining. To this end, an analytical approach was developed that incorporates analysis of nearshore wave transformation and wave-induced longshore sediment transport. The most effective means of quantifying incremental and cumulative physical environmental changes from sand dredging on the continental shelf is through the application of wave transformation numerical modeling tools that recognize the random nature of incident waves as they propagate onshore. Spectral wave models, such as STWAVE (*e.g.,* SMITH and HARKINS, 1997), REF/DIF-S (*e.g.,* CHAWLA *et al.,* 1994), SWAN (BOOIJ *et al.,* 1999), and others typically reproduce field measurements. As such, spectral wave transformation modeling was applied to evaluate the potential negative effects of sand removal from offshore borrow sites to coastal and nearshore environments. Although the interpretation of wave modeling results is relatively straightforward, evaluating the significance of predicted changes for accepting or rejecting a borrow site is more complicated.

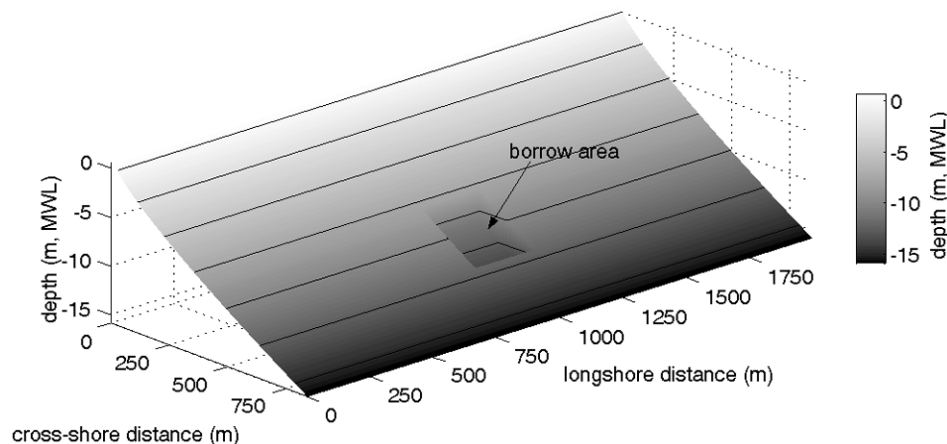A three-phase approach was implemented to evaluate the

Figure 1. Surface plot with 2.5-m contours of bathymetry grid used for idealized borrow site model runs.

potential physical effects of offshore sand mining on local wave and sediment transport processes. First, a standard method was developed to quantify the significance of changes associated with borrow site excavation and to determine the influence of borrow site geometry on wave refraction and sediment transport patterns. Because large spatial and temporal variability exists within the wave climate at a particular site, determination of physical impacts associated with sand mining must consider the influence of process variability. The second phase of the project focused on wave spectra development, wave transformation modeling, and coastal sediment transport calculations. The final phase addressed potential cumulative effects and significance of sand dredging from offshore sand borrow sites. A site-specific determination of acceptable limits of borrow site impacts relative to sediment transport potential was determined for each case.

WAVE AND SEDIMENT TRANSPORT PROCESSES

In recent years, there has been increased focus on the nearshore zone due to rapid development of coastal regions and the need to protect infrastructure from storms and long-term coastal erosion. This effort has concentrated on developing analytical tools to evaluate the transformation of waves in shallow water and to quantify sediment transport induced by breaking waves along the shoreline. Although improvements have been made, evaluation of coastal processes still requires a combination of analytical capability, interpretation of many complex and often apparently conflicting data sets, and experience gained from analyzing a variety of shorelines.

Nearshore Wave Transformation

Variations in seafloor elevation tend to dominate wave transformation as waves propagate into intermediate and shallow water. Although a small amount of energy is lost through bottom stresses (frictional drag), most nearshore wave transformation results from six processes: 1) refraction, 2) shoaling, 3) breaking, 4) diffraction, 5) reflection, and 6) wave-current interactions. These processes determine the size and incident angle of breaking waves, the dominant factors influencing nearshore sediment transport. Although minor wave diffraction and reflection may occur at an offshore borrow site, typically, the combined influence of wave refraction, shoaling, and breaking dominate transformation processes. Therefore, consideration of these three dominant processes represents the critical components of any spectral analysis used to evaluate alterations to a wave field associated with offshore sand mining.

Excavation of an offshore borrow site can alter wave heights and wave propagation direction. The existence of an offshore trough or trench may cause waves to refract toward the shallow edges of the borrow site. This alteration to the wave field changes local sediment transport rates, where some areas may experience a reduction in longshore transport and other areas may show an increase. The magnitude and significance of the change at the shoreline would depend upon the wave climate and the borrow site distance from shore. Analysis of wave modifications at an idealized borrow site was performed using STWAVE to illustrate how alterations in offshore bathymetry can modify existing wave conditions and resulting sediment transport processes. Figure 1 shows the configuration of a hypothetical borrow site, excavated into idealized bathymetry developed using straight and parallel contours and an Ay^m profile for southern New Jersey (DEAN, 1977). The idealized borrow site was located approximately 400 m offshore, centered on the -10 m (mean water level, MWL) bathymetric contour, with an excavation depth of 3 m below the seafloor. To evaluate a range of wave transformation possibilities, wave spectra centered at $-30°$, $-15°$, $0°$, $15°$, and $30°$ relative to shore normal were modeled, each with the same significant wave height and peak period, and having an equal percent occurrence (20%).

Figure 2 illustrates the influence of the idealized borrow site on nearshore waves for a single wave condition approaching the shoreline from $-30°$ relative to shore-normal. For this wave modeling case, the influence of the borrow site extends approximately 900 m alongshore measured at the breaker line. In addition, the maximum increase and decrease in
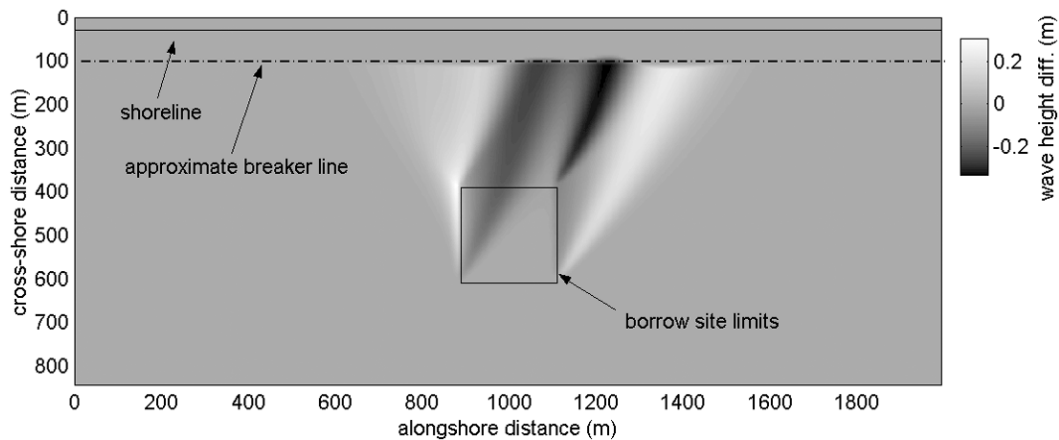
Figure 2. Shaded surface plot of wave height difference ($H_{post} - H_{existing}$) resulting from borrow site excavation (incident wave height of 1.2 m and period of 8 sec approaching the shoreline at 30 deg from shore-normal).

wave height resulting from borrow site excavation are of similar magnitude (approximately ±0.3 m). Waves propagating across the borrow site tend to refract toward shallow water along the edges, creating well-defined areas of wave energy focusing (increase in wave heights) landward of the borrow site. Due to the proximity of this borrow site to the beach, its influence on nearshore wave processes is more pronounced than for a sand borrow site further offshore. However, the nearshore location of the borrow site creates a rather limited longshore region of influence.

Nearshore Sediment Transport Patterns

Generally, beach shape is governed by relatively short-term events, such as severe storms. Large volumes of sand are eroded from the beach face and deposited nearshore during storm events. However, much of this material is recovered over longer time scales as lower energy waves move sand landward, causing the beach face to accrete. Seasonal trends in wave climate influence cross-shore sediment transport as well. Typically, large winter waves erode the beach face and mild summer waves build the beach. Because beach

shape is dynamic, the best estimate of a typical profile is the stable beach shape that forms when exposed to average wave conditions.

Although the influence of borrow site excavation on the wave field is a critical step in evaluating the physical effects associated with sand mining, an evaluation of wave field alterations alone does not directly provide information needed to assess potential impacts to the shoreline (*i.e.,* changes in sediment transport patterns). Calculation of longshore sediment transport potential for a series of wave cases provides a method for determining the extent and magnitude of alterations to nearshore processes. For the idealized borrow site (see Figure 1), a curve representing the annualized sediment transport potential along this model shoreline was generated (Figure 3). Transport values were computed using modifications to the CERC formula (*e.g.,* BODGE and KRAUS, 1991) proposed by KAMPHUIS (1990). The plot indicates that peak transport rates would increase to a maximum value at an alongshore distance of approximately 350 m from the center of the borrow site. These increases in sediment transport potential directed away from the borrow site are a result of wave focusing. In contrast, the small peaks in sediment transport potential between the two large peaks result from the shadowing of the borrow site created by wave condition combinations. For example, waves propagating over the borrow site from the right (15° and 30° wave conditions) create a shadow zone along the shoreline that is centered slightly to the left of the borrow site. This shadow zone is characterized by a decrease in left-directed sediment transport. Therefore, the overall effect is to create an increase in net right-directed (left-to-right) transport.

By computing the change in sediment transport potential over the shoreline distance ($\delta Q/\delta y$, where Q is the longshore sediment transport and y is the longshore coordinate), a normalized curve of anticipated shoreline change resulting from excavation of an offshore borrow site can be developed. Figure 4 illustrates normalized shoreline change resulting from wave conditions presented above. Due to wave focusing
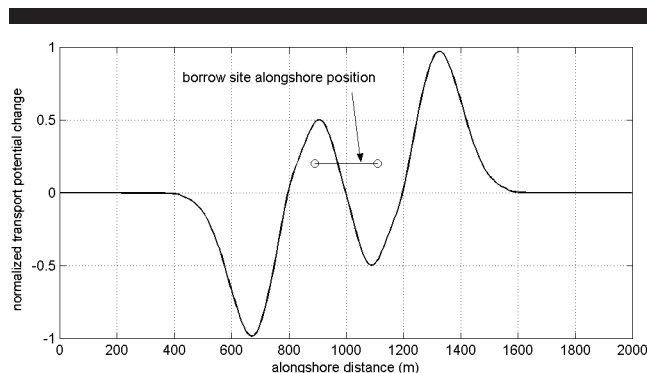

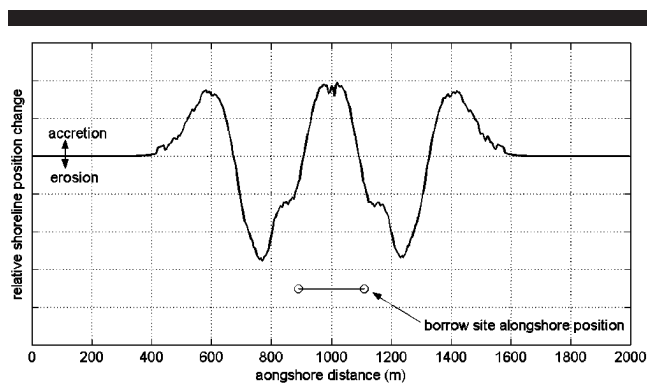Figure 3. Change in computed longshore sediment transport potential for idealized borrow site.

Figure 4. Computed cross-shore change in shoreline position based on modifications to longshore sediment transport potential by idealized borrow site.

caused by the borrow site configuration, increased erosion occurs along the shoreline on either side of the borrow site. Sand eroded from these two areas feeds the central shadow zone, as well as shoreline regions further from the borrow site.

DETERMINING SIGNIFICANCE OF BORROW SITE IMPACTS

As previously stated, calculated longshore sediment transport potential for a series of wave cases provides a method for determining the extent and magnitude of alterations to nearshore processes, but not the significance of changes for a particular coastline. For coastlines that experience large inter-annual variations in incident wave energy, alterations in the direction and quantity of longshore sediment transport will be highly variable as well. Therefore, a relatively large alteration in sediment transport, attributed to a proposed offshore sand mining project, may not be resolved in the observed shoreline change record due to high natural variability in the wave climate. For a shoreline site with a limited range of wave conditions (*e.g.,* a site dominated by ocean swell generated from a narrow direction band), alterations in natural sediment transport processes from proposed offshore dredging activities may be relatively large compared with natural variability. In the present study, a method based on historical wave climate variations, as well as local wave climate changes directly attributed to borrow site excavation, was developed to determine appropriate criteria for assessing the significance of alterations in longshore sediment transport resulting from dredging at offshore borrow sites.

Methods for Evaluating Borrow Site Impacts

One standard method for evaluating borrow site impacts is to perform wave and sediment transport modeling. Information developed from these modeling efforts is used to quantify potential physical environmental impacts associated with dredging activities. Although changes in sediment transport potential and wave energy flux associated with re-direction of waves generally are used as impact evaluation criteria, determining acceptable limits for these impacts is not a straightforward process. Existing methodologies have described alterations to the wave field at various locations (*e.g.,* directly landward of the borrow site, at a fixed reference line, at the breaker line; Basco, 1999), but the shoreline or breaker line appear to be most appropriate. In this manner, calculated longshore transport rates (based on wave modeling results) can be validated based on evaluation of observed shoreline change.

During 1999 and 2000, the U.S. Minerals Management Service (MMS) employed two different techniques for determining the significance of borrow site impacts associated with nearshore wave transformation. Basco (1999) developed a statistical approach to evaluate changes in wave climate at a pre-defined offshore reference line, as well as a method for determining the statistical significance of impacts. Although this method incorporates spectral wave modeling results and is statistically sound, it requires arbitrary user-defined limits. For example, rejection of the borrow site was based on greater than 50% of the reference line experiencing significant wave climate modifications. The 50% modification criteria and the length of the reference line are based on the user's judgment rather than scientific principles.

For borrow site studies in Alabama (Byrnes *et al.,* 1999) and New Jersey (Byrnes *et al.,* 2000), the significance of borrow site impacts was evaluated relative to potential error estimates associated with wave height and direction (Rosati and Kraus, 1991). Although use of wave information uncertainties offers a simple tool to address potential shoreline response to borrow site dredging, it also contains shortcomings. The method indicates the potential errors in wave information; however, it does not evaluate potential errors directly associated with the predictive wave models. If the same offshore wave field is defined for existing and post-dredging conditions, the error associated with wave measurements (direction and wave height) may not be the most appropriate indicator of borrow site impacts. It was concluded that if percent changes in longshore sediment transport caused by offshore sand mining were less than the percent error determined for wave height/direction estimates, the impact was insignificant.

Although the above methodologies provide reasonable quantitative estimates of significance associated with offshore sand mining, a new methodology for evaluating borrow site impacts that incorporates spatial and temporal changes in the wave field was developed. All three approaches use site-specific wave analyses as the basis for quantifying potential alterations to nearshore processes. However, the spatial and temporal variation method incorporates natural, site-specific variability in wave climate as a basis for determining significance.

Spatial and Temporal Variations Approach

Spatial (longshore) and temporal variations in local wave climate were determined for specific borrow sites to judge the significance of modeled impacts relative to site-specific wave characteristics. A shoreline that experiences a wide variety of wave conditions from year to year also experiences large
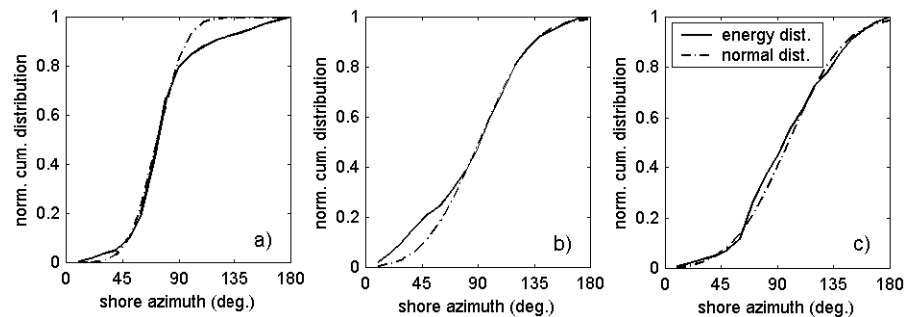
Figure 5. Comparisons of cumulative distributions of wave energy from three WIS stations located at a) Station 67, offshore New Jersey; b) Station 56, offshore North Carolina; and c) Station 14, offshore Florida. Normalized energy distributions based on wave approach angle to the shoreline (solid line) are plotted against normal distributions (dash-dot line) determined for each data set.

variability in sediment transport rates. Thus, the level of acceptable borrow site impacts would be relatively high. Conversely, a shoreline that experiences a limited range of wave conditions cannot accept the same level of borrow site impacts. Because the natural variability in inter-annual shoreline movements change along the coast, certain portions of the shoreline will be more tolerant of alterations to the wave climate and associated sediment transport patterns.

The significance determination method developed for this study relies on similar wave modeling results as those required for previous studies. Wave modeling is performed for several separate one-year periods to determine the characteristic inter-annual sediment transport variability along a shoreline. In this manner, temporal variations in wave climate are considered relative to long-term average conditions. Therefore, wave data records of adequate length (*i.e.,* cover several years) are required for a statistically significant analysis. For the east coast of the U.S., the Wave Information Study (WIS; HUBERTZ *et al.,* 1993) hindcasts of the U.S. Army Corps of Engineers (USACE) provided data records of appropriate length for use with the proposed method at several convenient offshore locations. If available, other sources of long-term wave data (*e.g.,* buoy data) could be used. In this study, wave modeling was performed at three locations for the entire 20-year wave hindcast time series and for 20 one-year blocks of the wave record. From these wave model runs, sediment transport potential curves were derived for average annual conditions (based on the full 20-year WIS record) and each one-year period (based on the 20 one-year wave records parsed from the full record). Based on this information, the average and standard deviation in calculated longshore sediment transport potential is determined every 200 m along the shoreline.

Assuming the temporal component of sediment transport potential is normally distributed across all approach angles to a shoreline, the suggested criterion for accepting or rejecting a potential borrow site is based on a range of one-half standard deviation ($\pm0.5\sigma$) about the mean (μ). This normal distribution simplifying assumption is based on comparisons relative to the distribution of wave energy approaching a shoreline. Figure 5 illustrates this comparison for three wave hindcast stations on the U.S. East Coast. The cumulative wave energy distribution by incident wave direction for each station is plotted with the normal distribution determined for each location. The comparison shows a reasonable fit for each of the three areas. If any portion of the sediment transport potential curve associated with a sand mining project exceeds $\pm0.5\sigma$ of the natural temporal variability about the sediment transport potential determined for existing (pre-dredging) conditions, the site would be rejected.

One standard deviation (σ) incorporates approximately 68% of the variability of a random variable, and $\pm0.5\sigma$ about the mean incorporates approximately 38% of the variability. Therefore, for σ determined from 20 one-year model runs, there is a 62% chance that the mean transport for any given year will fall outside the $\pm0.5\sigma$ envelope about the mean, and an 85% chance of falling outside this envelope during any two-year period. The envelope provides a basis for judging the impacts of a borrow site relative to natural variability of the sediment transport climate along a coastline. Because there is a greater than 50% chance that the transport computed for a particular year will fall outside of the $\pm0.5\sigma$ envelope about the mean, impacts determined for a particular borrow site that fall within this envelope likely will be indistinguishable from observed natural variations. For this reason, sites with large natural variation in wave climate and associated sediment transport potential could sustain greater impacts associated with an offshore sand mining project.

The initial application of this method (KELLEY *et al.,* 2001) used 1σ as the significance criterion, based on splitting the 20-year wave-hindcast record into five four-year periods, as opposed to 20 individual years for the present criterion. The standard deviation of transport computed using the 20-year record divided into five four-year periods is approximately 80% of 1σ determined for 20 individual one-year model runs. Therefore, the 0.5σ envelope was chosen because the $0.5\sigma+\mu$ level has an associated probability that is approximately 80% of the $1\sigma+\mu$ level, making the two significance envelopes roughly equivalent.

To ensure that spectral wave modeling and associated longshore sediment transport potential could be applied effectively to evaluate long-term alterations to the littoral system, a comparison of model predictions with observed shoreline change was performed. This analysis provided a semi-quan-

titative method for determining whether (a) longshore wave-induced transport is responsible for observed shoreline change, and (b) long-term shoreline change trends are consistent with the shorter-term (20-year) sediment transport potential analyses. An evaluation of model output was performed using a comparison of computed gradients in sediment transport with historical shoreline change data. The basis for this comparison is the relationship between shoreline movement and the longshore gradient of sediment transport (*e.g.,* DEAN and DALRYMPLE, 2002). Simply expressed, this relationship is

$$\frac{\partial Q}{\partial y} \propto \frac{\partial x}{\partial t} \qquad (1)$$

where Q is sediment transport, y is alongshore distance, x is the cross-shore position of the shoreline, and t is time. A comparison of results should illustrate similar trends in long-term shoreline change and transport potential computed using wave conditions that represent long-term average conditions. Good general agreement between these two quantities would suggest that the transport potential model reasonably represents long-term coastal processes for a given area, and thus, the model's ability to predict the likely impacts that would result from offshore dredging.

As a management tool, this methodology provides several advantages over methods previously employed to assess the significance of borrow site impacts. First, observed long-term shoreline change is compared with computed longshore change in sediment transport potential. Close comparison between these two quantities indicates that longshore sediment transport potential calculations are appropriate for assessing long-term natural change. Therefore, this methodology has a model-independent component (observed shoreline change) used to ground truth model results. Second, the method is directly related to sediment transport potential and associated shoreline change. Therefore, impacts associated with borrow site excavation can be directly related to their potential influence on observed coastal processes (annualized variability in shoreline position). Third, site-specific temporal variability in wave climate and sediment transport potential is calculated as part of the methodology. For sites that show little natural variability in inter-annual wave climate, allowable coastal processes impacts associated with borrow site dredging similarly would be limited, and *vice versa.* In this manner, the inter-annual temporal component of the natural wave climate is a major component in determining impact significance. Finally, similar to methodologies incorporated in previous MMS studies, the longshore spatial distribution of borrow site impacts is considered. However, the allowable limit of longshore sediment transport variability is computed from the temporal component of the analysis. Therefore, the final results of this analysis provide a spatially-varying envelope of allowable impacts in addition to the modeled impacts directly associated with borrow site excavation. The methodology accounts for spatial and temporal variability in wave climate, as well as providing a defensible means of assessing significance of impacts relative to site-specific conditions.
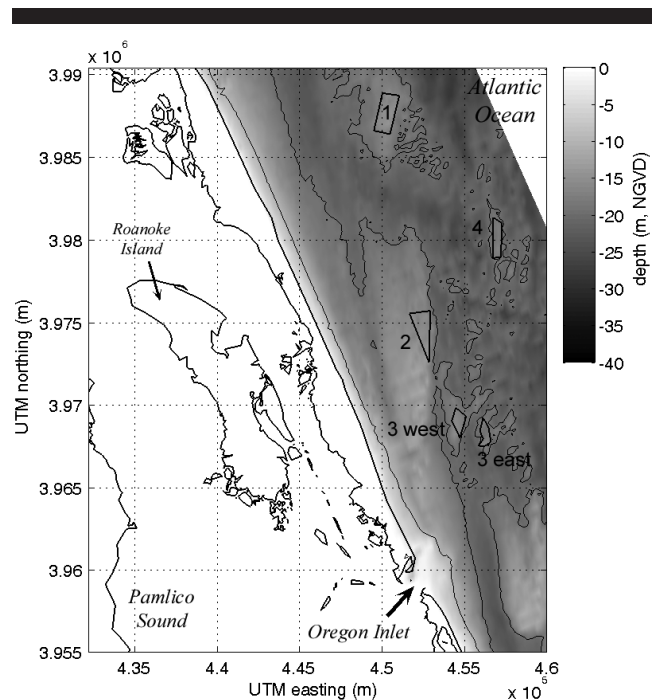

Figure 6. Bathymetry surface and borrow sites for offshore North Carolina. As designed, Site 1 is a 7.2 MCM borrow area, with a 3-m excavation depth; Site 2 has 5.8 MCM, with a 3-m excavation depth; Site 3 east has 1.4 MCM, with a 2-m excavation depth; Site 3 west has 2.5 MCM, with a 3-m excavation depth; and Site 4 has 2.3 MCM, with a 2-m excavation depth.

SEDIMENT TRANSPORT VARIATIONS AT PROPOSED BORROW SITES

The potential impacts of dredging at three proposed borrow sites offshore Dare County, North Carolina (Figure 6); offshore Martin County, Florida (Figure 7); and offshore Corsons Inlet, New Jersey (Figure 8) were evaluated within the context of natural variations in wave climate and sediment transport rates. For the North Carolina, Florida, and New Jersey examples, nearshore wave heights and directions along the shoreline landward of proposed borrow sites were estimated using the spectral wave model STWAVE to simulate the propagation of offshore waves to the shoreline. Offshore wave conditions used as input for wave modeling were derived from measured spectral wave data from offshore data buoys or hindcast simulation time series data from the USACE Wave Information Study (WIS; *e.g.,* HEMSLEY and BROOKS, 1989; and HUBERTZ *et al.,* 1993). In general, buoy data are the preferred source of wave information, because they represent actual offshore wave conditions rather than hindcast information derived from large-scale models. However, very few sites along the U.S. coast have wave measurement records of sufficient length to enable their use as a source of long-term information.

Offshore North Carolina

The shoreline north of Oregon Inlet in the North Carolina Outer Banks has been the focus of many previous monitoring
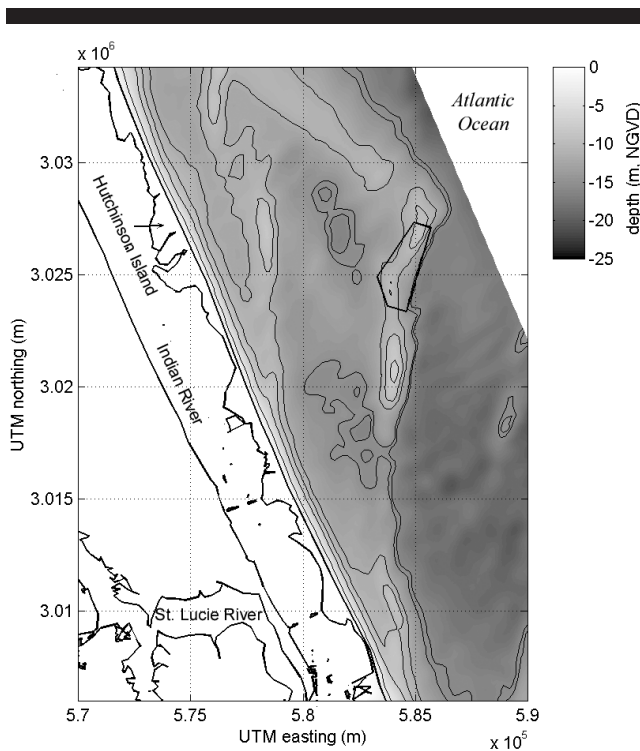
Figure 7. Bathymetry surface and borrow site for offshore Martin County, Florida. As designed, the site is a 24 MCM resource, with a 4.5-m excavation depth.

and modeling studies (*e.g.,* INMAN and DOLAN, 1989; LARSON, 1995; KIM, WRIGHT, and KIM, 1997; MILLER, 1999). In the present study, the potential impacts of five offshore borrow sites were investigated. Wave input conditions for simulations offshore North Carolina were developed using hindcast data from WIS station 56, located approximately 33 km northeast of Bodie Island, NC (HUBERTZ *et al.,* 1993). This WIS record covers a 20-year period from January 1976 to December 1995.

Historical shoreline change analysis provides a without-project assessment of shoreline response for comparison with predicted changes in wave-energy focusing at the shoreline resulting from potential offshore sand dredging activities. Because continuous measurements of historical shoreline change are available at 50-m alongshore intervals (see BYRNES *et al.,* 2003), model results (wave and sediment transport) at discreet intervals along the coast can be compared with historical data to develop process-response relationships for evaluating potential impacts. Shoreline data covering the periods 1849 to 1980 for Dare County, North Carolina were used to quantify trends. Methods for compiling and analyzing historical data sets are described in BYRNES and HILAND (1994). Alongshore variations in sediment transport were determined from computed values of transport potential for each shoreline for modeled existing conditions.

Trends in shoreline change generally agree with modeled transport gradients for the North Carolina coast north of Oregon Inlet (Figure 9). Results of both analyses illustrate a

stable to erosional shoreline, with an area of maximum erosion between 5 and 7 km north of Oregon Inlet. For the modeled transport gradient, there is an area of accretion located approximately 3 km north of the point of maximum erosion that is not indicated in the shoreline change analysis. This may be due to a lack of detailed nearshore bathymetry data for a 2 km section of coastline at this location. Bathymetry data used for developing the model grid was from the U.S. National Ocean Service (NOS) Geophysical Data System (GEODAS) database (NOS, 1998), but supplemental data digitized from a National Oceanic and Atmospheric Administration (NOAA) navigational chart were required in the area north of the inlet. Therefore, the bathymetry data in this area does not have a high level of detail as is available in the data used for adjacent sections of coast, and may affect the model results.

An exact match between the gradient in sediment transport potential and measured shoreline change was not expected due to the differing time scales of the two analysis techniques (several decades for shoreline change and 20 years for sediment transport potential). Significant migration of Oregon Inlet also may be responsible for some of the differences between observed and modeled shoreline change trends, where the peak in erosion likely has migrated south with the inlet. Therefore, the peak erosion area determined from the gradient of modeled transport potential, based on 20 years of recent wave information, may be more representative of present conditions than long-term shoreline change (based on more than 100 years of shoreline data). Overall, good agreement exists between observed shoreline change and longshore gradient in modeled transport potential. Minor differences between the two methods, especially in the region of maximum erosion, likely are due to long-term alterations (spanning several decades) in shoreline position and the historical migration of Oregon Inlet.

In Figure 10, the computed change in transport potential for the two modeled scenarios (where sites 3 east and 3 west were modeled alternately with sites 1, 2, and 4) falls within the $\pm 0.5\sigma$ significance envelope determined for this shoreline reach. Therefore, according to the impact significance analysis, the modeled borrow site configurations are acceptable without any additional stipulations. It is likely that if sites 3 east and 3 west were dredged at the same time as the other three sites, the resulting change in computed sediment transport potential would exceed the 0.5σ significance envelope. If the impacts did fall outside the envelope, a redesign of the borrow site configuration would be required to minimize the impact.

Offshore Eastern Florida

Results from the analysis of a single large borrow site offshore the east coast of Florida are shown in Figure 11. This proposed site is located approximately 5 km offshore, approximately 17 km north of St. Lucie Inlet. The resource site was identified to contain approximately 24 million cubic meters (MCM) of sand, with an excavation depth of 4.5 m (15 ft). Analyses of potential changes due to dredging at this site were conducted in a similar fashion as the previous analyses
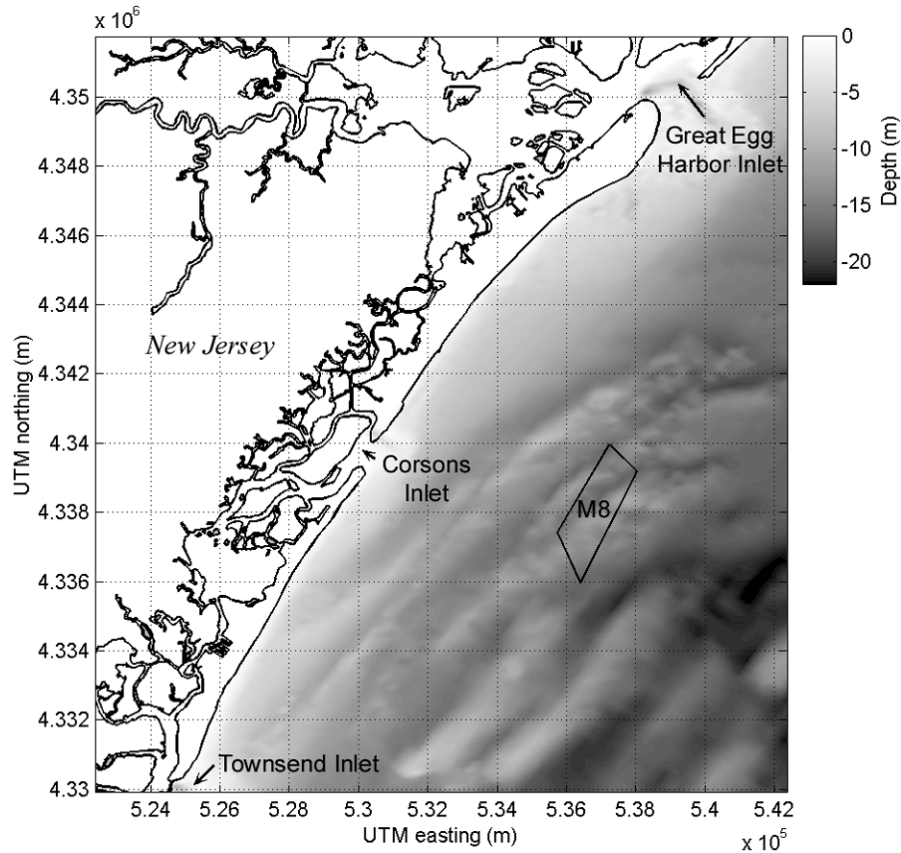
Figure 8.   Bathymetry surface and borrow site limits for offshore New Jersey.

presented for offshore North Carolina. Waves from WIS station 14 (HUBERTZ *et al.,* 1993) were used as input conditions for STWAVE model runs developed for this area. The $\pm0.5\sigma$ maximum influence envelope determined for this shoreline, along with the change in sediment transport potential resulting from dredging the borrow site, is shown in Figure 11. Unlike offshore North Carolina, the significance envelope is exceeded in an area updrift of the borrow site and nearly exceeded in an area downdrift of the borrow site. Because the resulting changes to longshore transport are determined to be greater than the allowable envelope for an approximate 2-km length of shoreline, this site would be rejected and would require redesign to reduce potential adverse modifications to the sediment transport regime. Additional model runs for this site indicated that an excavation depth of approximately 2 m would bring the transport variability caused by the borrow site within the $0.5\sigma+\mu$ envelope. Therefore, an approximate 12 MCM excavation at this site would be deemed acceptable based on potential impacts associated with coastal sediment transport processes.

Multiple Dredging Events Offshore New Jersey

As an example of evaluating potential cumulative effects associated with multiple dredging events at a single borrow site, wave and sediment transport modeling results were analyzed for multiple dredging excavation depths at Site M8, located approximately 7 km seaward of Corsons Inlet, New Jersey. This analysis applied the initial method for evaluating impacts, where the 20-year wave-hindcast record was split into five four-year periods, rather than 20 individual years. As described previously, the significance envelope resulting from this analysis technique is roughly equivalent to the $0.5\sigma+\mu$ envelope developed from splitting the 20-year wave hindcast record into individual years. Waves from WIS station 67 (HUBERTZ *et al.,* 1993) were used as input conditions for STWAVE model runs. The $\pm1\sigma$ maximum influence envelope determined for this area, along with changes in sediment transport potential resulting from a series of dredging depths at Site M8, are illustrated in Figure 12.

As the borrow site is excavated to greater depths (see Figure 12), the impact it has on wave-induced sediment transport potential along the shoreline increases. Exploring a range of reasonable excavation depths provides site-specific information regarding anticipated increase in impacts relative to dredging depth. Because of the proximity of the site to shore and its relatively large perimeter, deep excavations at Site M8 would have pronounced effects on modeled sediment transport patterns at the shoreline. Model runs were
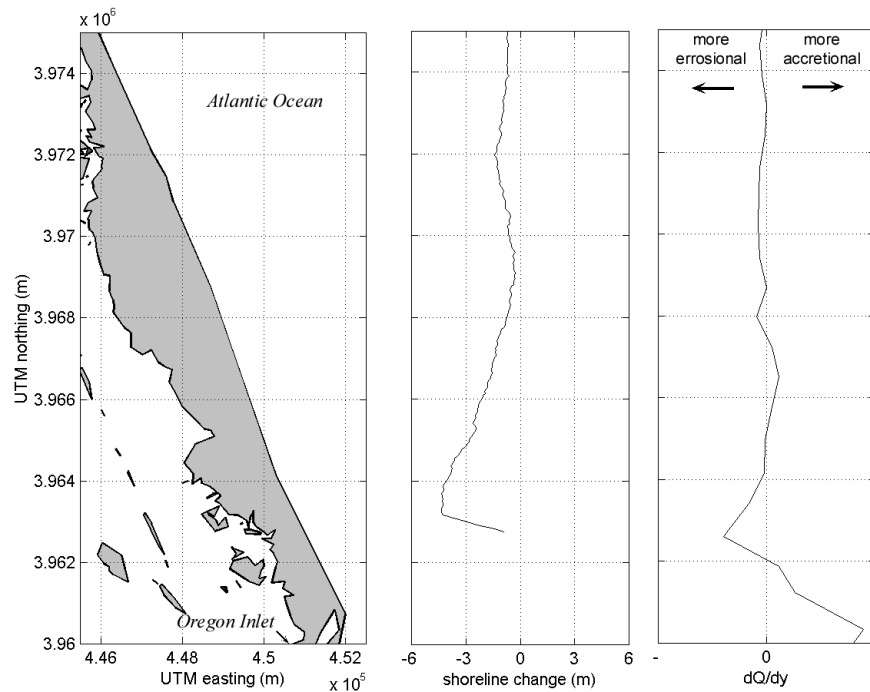
Figure 9. Comparison of historical shoreline change and gradient of modeled transport potential (δQ/δy) for the North Carolina shoreline.

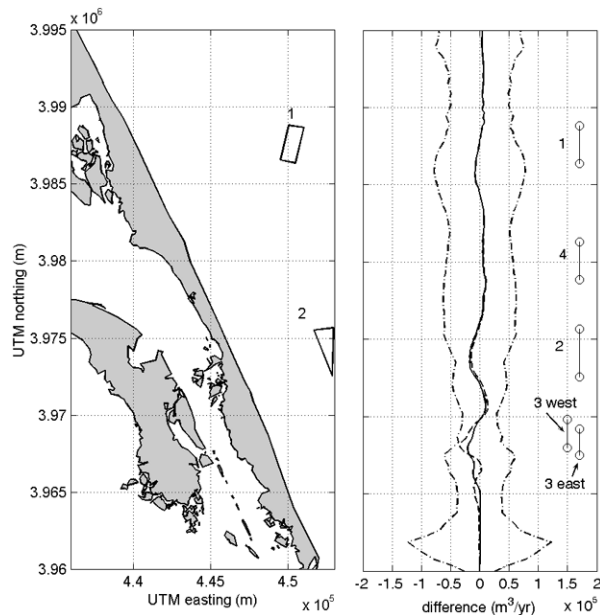Figure 10. Plot of transport potential difference between existing and post-dredging conditions, with the ±0.5σ maximum influence envelope (dash-dot line), for borrow sites located offshore North Carolina. The plot shows change in transport for Sites 1, 2, and 4, modeled with 3 east (solid black line) and 3 west (dashed line), separately. The longshore extent of each borrow site also is indicated. A positive difference in sediment transport potential is defined as an increase in north-directed transport.
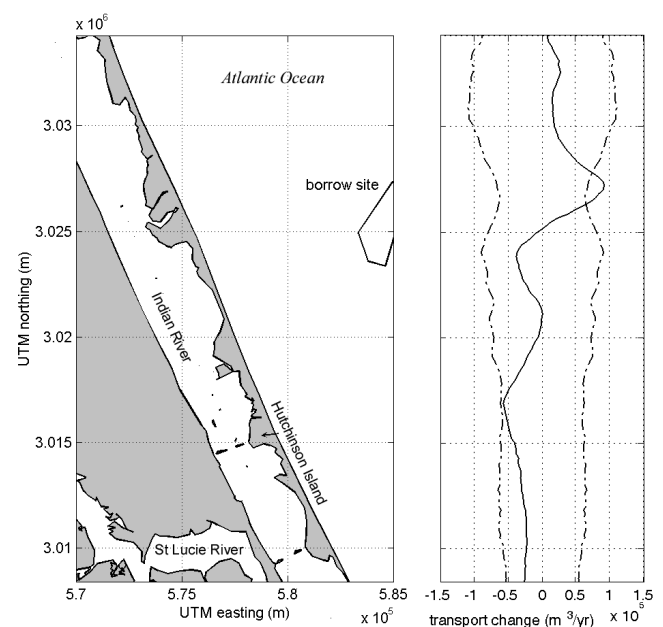

Figure 11. Plot of transport potential difference between existing and post-dredging conditions (solid black line), with the ±0.5σ maximum influence envelope (dash-dot line), for a single 24 MCM borrow site located approximately 5 km offshore Martin County, Florida. A positive difference in sediment transport potential is defined as an increase in north-directed transport potential.
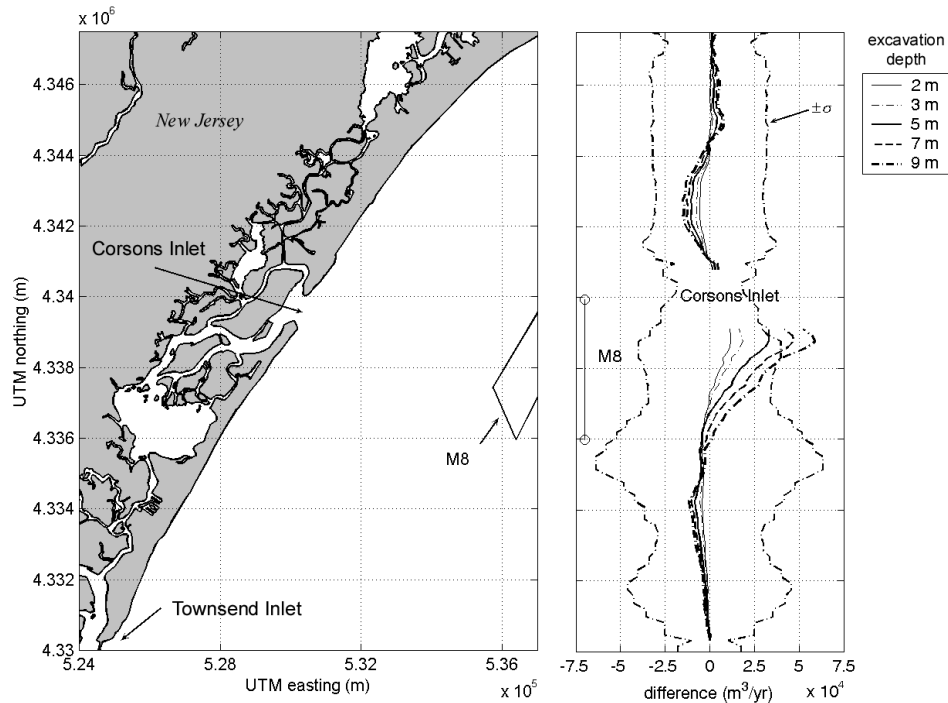
Figure 12.   Plot of change in sediment transport potential computed for five excavated depths at Site M8, offshore Corsons Inlet, New Jersey. The indicated dash-dot envelope represents the maximum transport influence that is allowed by the impact significance criterion, or ±1σ about the mean sediment transport potential for this case.

made for 2, 3, 5, 7, and 9 m excavation depths. The resulting change in sediment transport potential at the shoreline associated with each of these model scenarios is shown in Figure 12. Included with the plot of transport difference is the envelope of maximum change as defined by the impact significance criterion. Based on this information, excavation depths greater than 5 m would not be acceptable for this site, as the allowable limit criterion is exceeded along a portion of the shoreline south of Corsons Inlet.

DISCUSSION

To establish useful criteria for estimating impacts of sand mining on the nearshore littoral system, a comparison of sediment transport potential and long-term shoreline change was performed at each of three sites. The analysis provided a semi-quantitative method for determining whether long-shore wave-induced transport was responsible for observed shoreline change and whether long-term shoreline change trends were consistent with the 20-year sediment transport potential analysis. In general, the comparison indicated that the longshore gradient in computed wave-induced sediment transport followed similar trends as observed long-term shoreline change. Exceptions occurred at locations where STWAVE modeling was not applicable (areas where wave diffraction was important) or where wave-induced processes may not control sediment transport rates (in the vicinity of tidal inlets).

Because modeled longshore gradients in sediment trans-

port potential generally matched observed shoreline change trends, wave and sediment transport modeling provided a reasonable basis for evaluating long-term shoreline response associated with offshore sand mining. Because the natural variability in inter-annual shoreline migration changes along the coast, certain portions of a shoreline will be more tolerant of alterations to the wave climate and associated sediment transport. The method used to evaluate borrow site impacts provided a reliable technique for developing acceptable site-specific limits associated with changes in sediment transport potential.

Based on site-specific analyses for each of the three sites, an evaluation of impacts to the local wave and sediment transport regime ranged from insignificant to unacceptable. For offshore North Carolina, the two modeling scenarios indicated that the influence of excavating four borrow sites with a combined sand volume of between 16.7 and 17.8 MCM was deemed acceptable based on the significance criterion. As expected, excavation of Site 3 west had a greater impact on nearshore sediment transport patterns due to the large sand extraction volume, its proximity to the shoreline, and the relatively shallow water depths. Because it has been suggested that borrow sites located in close proximity illustrate additive impacts (KELLEY *et al.,* 2001), the influence of multiple sites on sediment transport along a coastline is an additive effect, rather than a more complicated non-linear effect or amplification. Therefore, it is likely that excavation of Site 3 east and Site 3 west would cause changes to the transport

potential to fall outside the significance envelope, and the excavation plan would be considered unacceptable.

Due to the relatively shallow water at the borrow site offshore Martin County, Florida (approximately 8 to 10 m), a 4.5 m excavation creates a pronounced effect on nearshore sediment transport processes. The maximum influence of this borrow site causes a reduction in net south-directed transport of nearly 100,000 m³/year. As a result of limited variability in incident wave climate, the influence of the 24 MCM sand mining scenario exceeds the allowable $\pm 0.5\sigma$ limit about the mean natural sediment transport potential (μ). By reducing the excavation depth to less than 2.3 m (an excavation volume of approximately 12 MCM), the influence of borrow site excavation on sediment transport potential falls within the significance criterion boundary. It is likely that re-orientation of the borrow site and/or expansion of the borrow site surface area with a decreased excavation depth also will decrease the impact to sediment transport process.

The quantitative methodology for assessing borrow site impacts can be used to determine allowable excavation depths. An example of this analysis was shown for the southern New Jersey coast, where the influence of dredging Site M8 to depths ranging from 2 to 9 m was evaluated. Due to the relatively narrow variability in wave-induced sediment transport potential (one standard deviation about the mean of approximately $\pm 40,000$ m³/year), it was determined that the maximum allowable excavation depth for this site is about 5 m. Although variability in sand transport potential along the shoreline of Martin County, Florida is significantly larger than off the coast of southern New Jersey (allowable limits about the mean of approximately $\pm 75,000$ m³/year compared to $\pm 40,000$ m³/year), excavation of the shallow shoal offshore Florida has a larger influence on wave refraction and associated sediment transport potential.

CONCLUSIONS

A quantitative method for evaluating the significance of changes to coastal processes that result from offshore sand mining is introduced and applied at three borrow site locations along the east coast of the U.S. As the basis for this method, temporal variations in wave climate and longshore sediment transport are evaluated relative to average annual conditions. The suggested criterion for accepting or rejecting a potential borrow site is based on a range of one-half standard deviation ($\pm 0.5\sigma$) about the mean. If any portion of the sediment transport potential curve associated with a sand mining project exceeds $\pm 0.5\sigma$ of the natural temporal variability about the sediment transport potential determined for existing conditions, the site would be rejected.

Sediment transport changes that fall within this envelope will be indistinguishable from observed natural variations. For this reason, sites with large natural variation in wave climate and associated sediment transport potential could sustain greater changes associated with an offshore sand mining project.

As a coastal management tool, this analysis procedure provides several advantages over methods previously employed to assess the significance of borrow site impacts. First, it has a model-independent component (measured shoreline change) with which to validate model results. Second, impacts associated with borrow site excavation can be directly related to their potential influence on observed coastal processes. Third, site-specific temporal variability in wave climate and sediment transport potential is calculated as part of the methodology. Finally, the method accounts for spatial and temporal variability in wave climate, and provides a means of assessing significance of changes relative to site-specific conditions.

LITERATURE CITED

BASCO, D.R., 1999. *A methodology and criteria to assess the impacts of sand volume removed in federal waters on the nearshore wave climate.* Coastal Engineering Center, Old Dominion University, Norfolk, VA.

BODGE, K.R; and KRAUS, N.C., 1991. Critical examination of longshore transport rate magnitude. *Proceedings, Coastal Sediments '91* (ASCE), pp 139–155.

BOOIJ, N.; RIS, R.C., and HOLTHUIJSEN, L.H. 1999. A third-generation wave model for coastal regions, Part I, Model description and validation. *Journal Geographical Research,* C4(104), 7649–7666.

BYRNES, M.R.; HAMMER, R.M.; VITTOR, B.A.; KELLEY, S.W.; SNYDER, D.B.; CÔTÉ, J.M.; RAMSEY, J.S.; THIBAUT, T.D.; PHILLIPS, N.W., and WOOD, J.D., 2003. *Collection of Environmental Data Within Sand Resource Areas Offshore North Carolina and the Implications of Sand Removal for Coastal and Beach Restoration.* U.S. Department of the Interior, Minerals Management Service, Leasing Division, Sand and Gravel Unit, Herndon, VA. OCS Report MMS 2000-056, Volume I: Main Text 257 pp. + Volume II: Appendices 70p.

BYRNES, M.R.; HAMMER, R.M.; VITTOR, B.A.; RAMSEY, J.S.; SNYDER D.B.; BOSMA, K.F.; WOOD, J.D.; THIBAUT, T.D., and PHILLIPS, N.W., 1999. *Environmental Study of Identified Sand Resource Areas Offshore Alabama: Volume I: Main Text, Volume II: Appendices.* U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division (INTERMAR), Herndon, VA. OCS Report MMS 99-0052, Volume I: Main Text 326 p. + Volume II: Appendices 132p.

BYRNES, M.R.; HAMMER, R.M.; VITTOR, B.A.; RAMSEY, J.S.; SNYDER, D.B.; WOOD, J.D.; BOSMA, K.F.; THIBAUT, T.D., and PHILLIPS, N.W., 2000. *Environmental Survey of Potential Sand Resource Sites: Offshore New Jersey.* U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division (INTERMAR), Herndon, VA. OCS Report MMS 2000-052, Volume I: Main Text 380 p. + Volume II: Appendices 291p.

BYRNES, M.R. and HILAND, M.W., 1994. Compilation and Analysis of Shoreline and Bathymetry Data (Appendix B). *In:* KRAUS, N.C.; GORMAN, L.T., and POPE, J. (eds.), *Kings Bay Coastal and Estuarine Monitoring and Evaluation Program: Coastal Studies.* U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Technical Report CERC-94-09, pp. B1–B89.

CHAWLA, A.; ÖZKAN-HALLER, H.T., and KIRBY, J.T., 1998. Spectral model for wave transformation over irregular bathymetry. *Journal of Waterway, Port, Coastal and Ocean Engineering,* 124, 189–198.

COMBE, A.J., III and SOILEAU, C.W., 1987. Behavior of Man-Made Beach and Dune Grand Isle, Louisiana. *Proceedings Coastal Sediments '87* (ASCE), pp. 1232–1242.

DEAN, R.G., 1977. *Equilibrium Beach Profiles: U.S. Atlantic and Gulf coasts.* University of Delaware, Department of Civil Engineering, Ocean Engineering Report No. 12.

DEAN, R.G. and DALRYMPLE, R.A., 2002. *Coastal Processes with Engineering Applications.* Cambridge University Press, Cambridge, UK.

FIELD, M.E. and DUANE, D.B., 1976. Post Pleistocene History of the United States Inner Continental Shelf: Significance to the Origin

of Barrier Islands. *Geological Society of America Bulletin,* 87, 691–702.

HEMSLEY, J.M. and BROOKS, R.M., 1989. Waves for Coastal Design in the United States. *Journal of Coastal Research,* 5(4), 639–663.

HORIKAWA, K.; SASAKI, T., and SAKURAMOTA, H., 1977. Mathematical and Laboratory Models of Shoreline Changes Due to Dredged Holes. *Journal of Faculty of Engineering,* XXXIV(1), the University of Tokyo, Japan, pp. 47–57.

HUBERTZ, J.M.; BROOKS, R.M.; BRANDON, W.A., and TRACY, B.A., 1993. *Hindcast Wave Information for the US Atlantic Coast.* WIS Report 30(AD A356 321), U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

INMAN, D.L., and DOLAN, R., 1989. The Outer Banks of North Carolina: Budget of sediment and inlet dynamics along a migrating barrier system. *Journal of Coastal Research,* 5(2), 193–237.

KAMPHUIS, J.W., 1990. Alongshore sediment transport rate. *Proceedings 22nd Coastal Engineering Conference* (ASCE).

KIM, S.C.; WRIGHT, L.D., and KIM, B.O., 1997. The combined effects of synoptic-scale and local-scale meteorological events on bed stress and sediment transport on the inner shelf of the Middle Atlantic Bight. *Continental Shelf Research,* 17(4), 407–433.

KELLEY, S.W.; RAMSEY, J.S., and BYRNES M.R., 2001. *Numerical Modeling Evaluation of the Cumulative Physical Effects of Offshore Sand Dredging for Beach Nourishment.* U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division (INTERMAR), Herndon, VA. OCS Report MMS 2001-098, 95 pp. + 106p. appendices.

LARSON, M., 1995. Model for decay of random waves in surf zone. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 121(1), 1–12.

MEISBURGER, E.P. and WILLIAMS, S.J., 1980. *Sand Resources on the Inner Continental Shelf of Cape May Region, New Jersey.* U.S. Army Corps of Engineers, Coastal Engineering Research Center, Miscellaneous Report 80-4, 40p.

MILLER, H.C., 1999. Field measurements of longshore sediment transport during storms. *Coastal Engineering,* 36(4), 301–321.

NATIONAL OCEAN SERVICE, 1998. Geophysical data system for hydrographic survey data. Version 4.0, National Ocean Service, Washington, DC.

ROSATI, J.D. and KRAUS, N.C., 1991. *Practical Considerations in Longshore Transport Calculations.* CETN II-24, U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS, 6p.

SMITH, S.J. and HARKINS, G.S., 1997. Numerical wave model Evaluations using laboratory data. *Proceedings Waves '97 Conference* (ASCE, Reston, Virginia).

WILLIAMS, S.J., 1987. *Geologic Framework and Sand Resources of Quaternary Deposits Offshore Virginia, Cape Henry to Virginia Beach.* U.S. Geological Survey, Open-File Report 87-667, 60p.